A D04107229 Craig Taylor
01

1234

MEMORANDUM REPORT

OF

RO MEDICAL LABORATORY

15
3-8-1

AIR TECHNICAL SERVICE COMMAND
ENGINEERING DIVISION

WRIGHT FIELD, DAYTON, OHIO

SUBJECT

HUMAN TOLERANCE FOR SHORT EXPOSURES TO HEAT

20061018058

SERIAL No.: TSEAL-3-695-49A	DATE: 28 FEBRUARY 1945	COPY No.:

No. of Pages: 31

ARMY AIR FORCES
[redacted]
HEADQUARTERS, AIR TECHNICAL SERVICE COMMAND
ENGINEERING DIVISION
MEMORANDUM REPORT ON

Lt. C. L. TAYLOR
lv (TSEAL-3C)

Date 28 February 1945.

SUBJECT: Human Tolerance for Short Exposures to Heat.

[redacted] Aero Medical Laboratory

Contract or Order No.

SERIAL No. TSEAL-3-695-49A

Expenditure Order No. 695-40

A. PURPOSE.

1. To establish the maximum tolerable limits of temperature and humidity in cabins of high speed fighter aircraft of unconventional type.

2. To present the results of a preliminary investigation of heat tolerance at high environmental temperatures and humidities.

B. FACTUAL DATA.

1. The development of very high speed fighter aircraft poses the problem of excessive cockpit temperatures, particularly in fast sweeps at low altitude. The heat arises from three sources, namely: solar radiati[illegible] transmitted through the plexiglas bubble canopy; friction of the air pass[illegible] over the surface of the fuselage; and the heat of ram pressure. For exa[illegible] the last named phenomenon may cause a temperature rise above OAT of 29°F [illegible] a speed of 400 m.p.h.; this value increases to 45°F at 500 m.p.h. and t[illegible] 64°F at 600 m.p.h. If to this is added another 10 to 15°F effective tem[illegible]ature due to solar radiation, cabin temperatures in excess of 150°F may b[illegible] expected even when ambient temperatures are not higher than 90 to 100°F.

2. Since the duration of exposure to these high temperatures is expected to be short, 15 to 30 minutes at a maximum, as limited by the tactical use of the airplane and the fuel supply, steady states of human heat balance are not required. The biophysical problem is to determine points on a duration-intensity curve which are tolerable for Air Force personnel. In selecting these points, it must be assumed that pilots are not heat acclimatized, and that they represent a range of constitutional and fitness types.

3. Human tolerance for heat is determined by factors which can be classified as environmental and physiological:

a. The basic environmental factors are four: dry bulb temperature, mean radiant temperature, vapor pressure of the atmosphere, and air movement. With the special case of aircraft cabins in mind, the first two factors may be represented by dry bulb temperature, and air movement may be eliminated as a variable by utilizing the moderate value of 3.5 m.p.h. The possible error involved in these assumptions is small, and this simplification of the problem is justified by the observation that air movements in aircraft cabins are generally in the range 2 to 5 m.p.h., the average of which was used in these experiments. We have, therefore, two main variables, dry bulb temperature and vapor pressure. The first of these influences heat balance by determining the rate of transfer of heat from the environment to the body by radiation and convection. The second factor acts to limit the evaporative heat loss, so that at high vapor pressures, which approach the vapor pressure of sweat, the amount of radiative and convective heat gain which can be balanced by evaporation is correspondingly reduced.

b. The strain upon the physiological makeup of the body may be measured by the following:

(1) The primary physiological change is an increase in body heat content and concomitant temperature rise. This phenomenon is measured by internal (rectal) temperature.

(2) The secondary physiological changes occur in the homeostatic mechanisms of temperature regulation and circulation. The acceleration in heart rate, the rate of sweat loss and the skin temperature, serve to measure the degree of strain on the homeostatic mechanisms.

(3) Finally, appearance, subjective state, functional efficiency, and presence or absence of symptoms of heat exhaustion in the exposed individual must be taken into account in evaluating the various levels of body temperature and homeostatic response.

4. Three steps have been taken in defining tolerance limits in the present investigation:

a. Experiments were conducted to establish levels of physiological response and the combinations of dry bulb temperature and vapor pressure which produce equal physiological response. In this primary series

four previously acclimatized subjects participated in 16 one-hour exposures in the All-Weather Room. The selected environments ranged from 90 to 160°F and from 5 to 90 per cent relative humidity. The subjects were clothed in 80-20 cotton-wool underwear and light byrdcloth flying coveralls. They sat at rest during exposure. Sweat loss, heart rate and skin and rectal temperatures were taken before and three times during the exposure. A full description of these experiments is given in Appendix I and the data are presented in Tables 1-3.

b. The data from the first series were treated to yield an equation from which the level of physiological response could be predicted from the environmental variables (Table 4). The levels (L) are given by the formula:

$$L = .047 \text{ (dry bulb, °F)} + .057 \text{ (vapor pressure, mm. Hg)} - 7.31$$
$$= .085 \text{ (dry bulb, °F)} + .057 \text{ (vapor pressure, mm. Hg)} - 5.82$$

From these equations, levels of equal physiological response were drawn on a temperature-humidity-vapor pressure chart (Figure 1). It should be expressly understood that these equations serve primarily to express the regression of vapor pressure on dry bulb temperature at constant level of physiological response. Their validity rests upon the results of the verification tests described next.

c. Tests were then run to establish the tolerability of the environments producing specified levels of physiological response for selected durations of exposure, and to confirm the equivalence of the predicted temperature-humidity combinations. After consideration of the data and general experience with the first series of tests, and after conducting a few exploratory experiments, lines 4 and 5 (Figure 1) were tentatively chosen as 60- and 30-minute tolerance limits. Fourteen subjects were then tested at selected points on line 4, and nine subjects similarly on line 5. These tests were conducted exactly as described for the first series, except that the length of exposure on the line 6 was limited to 35 minutes. A description of these tests is given in Appendix II and Tables 5 and 6.

5. On the basis of the results from the verification experiments, which confirmed the general validity of the prediction equations in regard to both the reciprocal relationship of temperature and vapor pressure, and the selection of tolerance levels, a three-fold classification of tolerance lines was decided upon. The environments were classified as tolerable, marginal, or intolerable for specified durations of exposure for individuals having the constitutional and fitness qualifications of Air Force pilots. A discussion of the basis for this classification is found in Appendix III.

6. Since in all hot climates, whether dry or humid, the atmospheric vapor pressure probably does not exceed 30 mm. Hg, it is possible to define tolerance limits solely in terms of temperature for the special case of temperature rise with constant absolute humidity in aircraft cabins. This directs attention to the unique problem of the cockpit atmosphere wherein the humidity effect is relatively restricted, and permits a practical simplification of the tolerance classification. (Appendix III.)

C. CONCLUSIONS.

1. The requirements for aircraft cabins relative to ventilation and cooling have been reduced to two variables: dry bulb temperature and relative humidity. These requirements for unconventional type aircraft are given in the following table:

Limiting Environments		Physiological Level					
		Line 3*		Line 4*		Line 5*	
		°F	°C	°F	°C	°F	°C
Relative Humidity (%)	10	138	59	145	63	153	67
	30	122	50	127	53	133	56
	50	112	44	117	47	122	50
	70	106	41	110	43	114	46
	90	101	38	105	40	108	42
Physiological Zones:							
30 minute exposure		Tolerable		Tolerable		Marginal	
60 minute exposure		Tolerable		Marginal		Intolerable	

2. On the basis of climatic data now available, which show that atmospheric vapor pressure may not be expected to exceed 30 mm. Hg, humidity may be eliminated as a variable, and the requirements for ventilation and cooling of unconventional type aircraft stated solely in terms of dry bulb temperature, as follows:

Physiological Level	Temperature		Physiological Classification	
	°F	°C	30 Min. Exposure	60 Min. Exposure
Line 3*	120	49	Tolerable	Tolerable
Line 4*	130	54	Tolerable	Marginal
Line 5*	141	61	Marginal	Intolerable

* See Figure 1.

Eng. Div. Memo. Report
No. TSEAL-3-695-49A
28 February 1945.

D. **RECOMMENDATIONS.**

1. It is recommended that AAF Specification No. R-40659 be amended to require, on unconventional type aircraft, limits of cabin temperature in accordance with the conclusions of this report.

2. It is recommended that these studies be continued (a) to add to the number of Air Force personnel tested, (b) to include variations in air movement, and (c) to assess the additional effect of solar radiation.

Distribution:
Randolph Field, Texas (262)
A, B, C, D, E, F, & G
Air Surgeon:
Bur. of Standards (1)
Bur. of Aeronautics (1)
Air Marshall H. E. Whittingham (1)
Dr. Sid Robinson, Dept. of Physiol. (1)
Univ. of Indiana
Climatic Research Lab., Lawrence, Mass. (1)
Dr. E. F. Adolph, Dept. of Physiol. (1)
Univ. of Rochester, Rochester, NY
Harvard Fatigue Laboratory (1)
Dr. John Lawrence (1)
Univ. of Calif.
~~Distribution~~
Personal Equip. Lab.:
Test Control Br. (TSEAL-5B) (1)
Clothing Br. (TSEAL-5C) (1)
Equip. Lab.:
Heating, Cooling & Ice Prevention Unit (1)
Col. Garman (TSESE) (1)
Col. F. R. Cook (TSESE) (1)
Power Plant (TSEPL-5C) (1)
Attn: Maj. Sadler
Materiel & Services (1)
O.C. & R. (1)

Prepared by CRAIG L. TAYLOR, 1st Lt., A.C.

A. P. Gagge

Approved by A. P. GAGGE, Lt. Col., A.C.
Chief, Biophysics Branch.

for Marius P. Kelsey Maj AC

Approved by W. RANDOLPH LOVELACE, II
Colonel, Medical Corps,
Chief, Aero Medical Laboratory.

Concurrence:

APPENDIX I

MAIN SERIES OF TESTS.

A. SUBJECTS.

Four subjects, whose characteristics are given in Table I, carried out the 48 one-hour tests in the main series. They are normally healthy and active young men with no defects which would make them unfit for military service. Several body types are represented, but extremes are lacking. No dietary or other hygienic control was exercised, but no subject was tested during any condition which deviated significantly from his health norm.

Since it is well known that acclimatisation to heat proceeds rapidly during initial exposure, and physiological responses to hear are markedly changed during this period, the four subjects underwent a preliminary acclimatization regime of four days. During this time, four hours each day were spent in the All-Weather Room at 120°F and 20 per cent relative humidity. Half of this time was devoted to treadmill walking, and half to resting, but no physiological measurements were made.

B. ENVIRONMENTAL CONTROL.

The All-Weather Room at the Aero Medical Laboratory was the scene of all tests. The room temperatures are obtained by recirculating the air over electric heating coils, and humidification is accomplished by spraying hot water under pressure through atomizing jets into the room. Both temperature and humidity conditions are under automatic control, but more precise adjustment may be made manually. The environmental conditions were set up during the hour preceding the tests, and only minor readjustments were required during the test period. The polished stainless steel walls quickly approach air temperature, and the air-wall temperature differential seldom exceeds ±3°F, thus assuring that the radiant and air temperature environments are substantially equal.

Dry and wet bulb temperatures were determined previous to and three times during the tests with a Friez fan-ventilated hygrometer. The temperature and humidity data of Tables II, V, and VI are the averages from the three observations made during the course of the test. Relative humidity and vapor pressure were obtained by entering standard tables with the dry and wet bulb temperature data*.

Turbulent air motion in the All-Weather Room under the conditions of these experiments is equivalent to 3.5 miles per hour.

* Marvin, C.F., Psychrometric Tables, Weather Bureau, U. S. Dept. of Commerce, U.S. Govt. Print. Off., 1941.

Eng. Div. Memo. Report
No. TSEAL-3-695-49A
28 February 1945.

Appendix I
Main Series of Tests.

C. PHYSIOLOGICAL MEASUREMENTS.

Heart rates were obtained by 30-second pulse counts. Weight loss was obtained by difference from the nude weight of the subject, measured before and after the hot-room exposure on a Fairbanks platform scales, sensitive to one ounce. All articles of clothing (thermocouple underwear, light byrdcloth flying coverall, and sox) were weighed to a gram on a Toledo scales before and after the test. Skin temperatures were obtained from thermocouples placed on the surface of forearm, chest, lower back, rump, and lower leg. Mean skin temperature is the simple average of readings from these points. Rectal temperature was obtained from readings of a thermocouple inserted to a depth of five inches.

D. EXPERIMENTAL ROUTINE.

The subjects stripped, were weighed, and then donned previously weighed clothing. They sat at rest for 15 to 30 minutes under normal room conditions (dry bulb, 75-80°F, relative humidity, 25-40 per cent) during the latter part of which pulse, and skin and rectal temperature data were taken.

After entering the All-Weather Room, the subjects took sitting positions, and physiological measurements were made at 20, 40, and 60 minutes of exposure. The tests were terminated at 60 minutes, or when conditions became intolerable, and the subjects were forced to leave the hot room. The symptoms which terminated experiments before the scheduled time are discussed in Appendix III

Sixteen exposures were accomplished at dry bulb temperatures ranging from 92 to 158°F, and relative humidities from 7 to 88 per cent. In six tests all 4 subjects were tested; in the remaining, two or three were used. The environmental conditions of the tests are detailed in Table I

E. RESULTS.

Since in the eight most extreme exposures one or more of the subjects were unable to complete the 60 minutes, the values at 40 minutes were chosen to characterize the physiological response to the particular environment. In this way all the data could be used. The average data for the four measures, heart rate, skin and rectal temperatures, and water loss data, in the cases of the early terminated tests, were calculated to a 60-minute basis, but were not included in the Index because of the doubtful validity of the recalculated water losses. Accordingly, the 40-minute average values for heart rate, and skin and rectal temperature were used in the computation of a level of physiological response (L).

Eng. Div. Memo/ Report
No. TSEAL-3-695-49A
28 February 1945.

Appendix I
Main Series of Tests.

The three physiological variables were given an equal weighting, by expressing each as a deviation from its mean, and averaging these deviations to obtain L. Two environmental values were used in the analysis, dry bulb temperature and vapor pressure of the air. Zero order correlations were then computed, yielding positive coefficients between L and dry bulb, and L and vapor pressure, and a negative correlation between dry bulb and vapor pressure. The latter relation is due to the fact that high dry bulbs and high vapor pressures in combination are intolerable and no data could be secured under these conditions. The high partial and multiple correlations indicate that dry bulb and vapor pressure are linearly related to L and constitute the essential environmental variables*. A regression equation was then formulated from which L may be predicted from vapor pressure and dry bulb temperature.

From this equation lines were plotted on a dry bulb-vapor pressure chart at five values of L, namely, at -1.0, -0.5, 0.0, 0.5, and 1.0 in standard deviation units, respectively labeled lines 1-5 (Figure 1). Curves of relative humidity are shown for reference. The original L data (average for 2-4 subjects at each exposure) were then plotted on Figure 1 to indicate the relationship. The general trend is apparent, namely: as dry bulb increases, the tolerable vapor pressure decreases. The correspondence between L values and the discrete data is only general, but the only point markedly out of line is an L of -0.55 which should be close to the 2 line instead of above and to the right of the 3 line. No reason can be given for this discrepancy.

The values at five levels of physiological response based on 40 minutes of exposure are displayed in the following tabulation:

Measure \ L	5	4	3	2	1
Heart Rate	134.0	125.0	116.0	107.0	98.0
Skin Temperature	101.4	100.4	99.5	98.6	97.6
Rectal Temperature	100.4	100.0	99.5	99.0	98.6

* It is realized that the above treatment of the data violates certain statistical rules, e.g., intra-individual and inter-individual data are treated together, and the correlations are based on a small number of variates. Consequently, statistical inferences concerning reliability and generalization cannot be justified, and the results must be judged in the light of the data obtained, and the outcome of check tests described in Appendix II.

Appendix I
Main Series of Tests.

Figure 2 shows the data analyzed in another way. The 16 tests were serialized according to L and segregated into 4 groups of four tests each. Average physiological responses for each group are plotted showing both the trend during the exposure and the difference in magnitude of response. Groups III and IV display an equilibrium in skin temperature after the initial rise, only slight rises in rectal, and moderate elevations of heart rate. The average responses of groups I and II, on the other hand, rise to greater heights in all variables. The differences between them reflect the small divergence in their mean L indices.

Weight losses for the groups in grams per square meter of body surface generally correspond in relative magnitude to the values for the other physiological variables. This indicates that distrust of the weight loss data because of incomplete experiments was probably unfounded, but it also shows that weight loss correlates well with heart rate and the body temperatures. Omission of weight loss from L, therefore, can have made little difference in its characteristics.

APPENDIX II

CHECK TESTS.

The primary purpose of the Main Series was to establish the relationship between physiological responses and the environmental influences. The shape of this relationship is defined by the formula:

$$L = -7.31 + .047 \text{ (dry bulb)} + .057 \text{ (vapor pressure)}$$

With this formula one may determine the various combinations of the environmental conditions which will produce a given L or any of its physiological correlates. The slope of relationship being defined, the selection of a physiological response level is dictated by consideration of the specific problem at hand. In the present instance the purpose is to define tolerance limits for short exposures. Over such short periods heat balance need not be attained as shown by curves in Figure 2, and the critical issue is how long exposure may be continued before critical hyperthermia develops. It was decided to define two tolerance limits, 60 and 30 minutes in duration, and these for men totally unacclimatized to heat.

A. SIXTY-MINUTE TOLERANCE LIMIT

After some inspection of the Main Series data, the 4 line was tentatively chosen as the 60-minute tolerance limit for unacclimatized men. Fourteen subjects were selected as available from the laboratory roster. All but one were novices in hot room studies. The environmental conditions at the selected points along the 4 line which were chosen for test and the physiological responses are given in Table V, and plotted in Figure 4.

Two criteria should be applied in the evaluation of these data. The first pertains to the setting of the physiological level. That the choice of the 4 line as the 60-minute limit was substantially correct is shown by the facts: (1) all subjects but one were able to complete the period without symptoms of heat exhaustion, collapse, or any of the extreme sensations which forced subjects to leave intolerable environments in the Main Series*; and (2) the terminal heart rates and skin and rectal temperatures in this series (see Figure 6) agree reasonably well with the mean values for line 4, shown in the tabulation in Appendix I.

* See Appendix III.

Appendix II
Check Tests.

The second criterion is the constancy of physiological response along the selected line. To test this, the data have been plotted serially by experiment number which is also the order of progression from hot-dry to hot-humid conditions. Since there is considerable scattering of the data about the average lines in all the physiological measures, an equated mean deviation score (the average of physiological values expressed as deviations from their means) was computed for each experiment. Ideally, these equated mean values should fall on a line through their mean. It can be seen from Figure 4 that they fail to do so particularly in the cases of numbers 6 through 9 which show lower values. The predicted L's for the environmental conditions of the tests, as calculated from actual dry bulbs and vapor pressures obtained*, are shown in the figure, but the lack of correlation with equated means offers no explanation for the latter. The discrepancies in the equated means must therefore be attributed to individual variability. Any possible error, and the evidence is that it cannot be large, is on the conservative side.

As a further check on the validity of the line, negative storage values were computed for each case, according to the formula:

$$S = \frac{.83 \times W \times (.67\ dT_r + .33\ dT_s)}{SA}$$

where,
- S = stored heat accumulation (Kcal. per sq. meter)
- $.83$ = specific heat (Kcal. per Kg. per degree C)
- W = body weight in Kg.
- dT_r = difference between pre-exposure and terminal rectal temperatures (°C)
- dT_s = difference between pre-exposure and terminal skin temperatures (°C)
- SA = surface area (sq. meters)

These values, plotted in Figure 7, scatter about a mean of 71, and with the exception of case 1, there is no discernible correlation with dry bulb temperature. This means that the selected temperature-humidity conditions have an approximately equal effect upon heat balance.

B. THIRTY-MINUTE TOLERANCE LINE.

A similar line of proof was used to validate a 30-minute tolerance limit. Two facts led to the selection of the 5 line as a 30-minute tolerance limit. (1) The average L of the eight tests in the Main Series which were terminated short of 60 minutes of exposure was + 1.0, stand. deviation (line 5), and (2) no subject quitted the room in less time than 30 minutes.

* Absolute precision in temperature and humidity control could not be attained in the hot room, consequently, the average of three wet and dry bulb temperatures represent the exposure environment.

Appendix II
Check Tests.

This line is therefore marginal for the acclimatized subjects for exposure times of 40 minutes or longer. A check series of tests was conducted on 9 subjects at selected points along the 5 line. The data are given in Table VI and the physiological values are plotted in Figure 5. Again these data may be evaluated in accordance with two criteria; (1) the levels of physiological response defined for 1.0 Index (see tabulation in Appendix I) were approximated by terminal values in the 30-minute check series (see Figure 7). Thus heart rate in the latter case is but 6 beats lower, skin temperature about the same, and rectal temperature 0.3° F lower. (2) The equated mean responses similarly test the validity of the slope value of the L formula (Figure 6). Again, considerable scattering of values about the means is found. The most notable deviations are the pronounced weight losses of subjects 5 and 8, who are heavy men weighing 220 and 202 pounds respectively. Even when weight losses were calculated to unit surface area these men sweated much more than the more average sized men. Consequently, the sweat losses markedly elevated the equated means of these two subjects. Disregarding these cases then, the remaining equated means scatter about their average line without displaying a clear-cut departure from zero slope.

Storage values were also computed for the nine subjects in the 30-minute series. These are plotted in Figure 7. The storage values scatter about an average of 70 k-cal. per square meter without significant correlation with dry bulb temperature, attesting to the equivalent effect of these environments upon heat balance.

APPENDIX III

DISCUSSION

A. CRITERIA OF HEAT TOLERANCE

From a purely physical standpoint the human body may be viewed as a moist, black, and internally-heated object which carries out thermal interchanges with its environment in accordance with the heat balance equation;

$$M \pm S \pm R \pm C = E$$

where, M = heat production
S = change in heat content of the body
R = radiant heat transfer
C = convective heat transfer
E = evaporative heat transfer.

M is always a source of heat and E a loss of heat, but the signs of S, R, and C are so chosen that in an environment colder than the body, $M + S = E + R + C$, and in an environment hotter than the body, $E + S = M + R + C$. The latter is pertinent to the present situation, except for the added factor of the insulation of clothing which tends to reduce radiative and convective gain and to alter the characteristics of evaporative cooling. No attempt has been made to strike a thermodynamic balance in the present data because certain elements, such as effect of wetness on the clo of clothing and on the efficiency of evaporation, have not been determined.

However, the heat balance is not a measure of tolerance, and the physiology of the human body is too complex to permit of a formulation in physical terms alone. Of the physical factors, only S, the change in stored heat, is an index of the strain on physiological mechanisms. With rise in stored heat -- this is positive in the sense of accumulation in the body, but negative in the thermodynamic equation -- body temperature rises, stimulating sweat production, and rises in metabolic rate and heart rate. Up to a certain point this condition of hyperthermia is adaptive, since augmented sweat production increases evaporative heat loss, and acceleration of heart rate increases peripheral circulation so that the blood may more readily give up its heat at the skin. These responses may therefore be used as physiological indices of the effect of heat upon the body, providing a scale of heat load with which may be correlated, on the one hand, the environmental variables, and on the other hand, the various unmeasured physiological and psychological reactions by which we judge the exposure as tolerable or intolerable.

Eng. Div. Memo. Report
No. TSEAL-3-695-49A
28 February 1945.

Appendix III
Discussion.

Four variables have become standard in the assessment of the physiological effect of hot environments: (1) heart rate, (2) average skin temperature, (3) rectal temperature, and (4) sweat loss. Applications including two or more of these variables appear in papers by Adolph and Dill (1938), Robinson et al. (1943), Taylor et al. (1943a) and (1943b), and Robinson (1944). The latter author has integrated these into the following Index of Physiological Effect (E_p):

$$E_p = \frac{100\,(H_3 - H_1)}{H_2 - H_1} + \frac{100\,(S_3 - S_1)}{S_2 - S_1} + \frac{100\,(R_3 - R_1)}{R_2 - R_1} + \frac{100\,(W_3 - W_1)}{W_2 - W_1}$$

where the symbols H, S, R, and W mean heart rate, skin temperature, rectal temperature, and sweat loss, respectively, and the subscripts 1, 2, and 3 refer to responses at the minimal, maximal, and intermediate environments. This provides a scheme for rating all environments in terms of their observed physiological effect as a per cent of the effect at the most extreme environment the subject can tolerate. Robinson has presented tolerance contours in terms of Physiological Effect plotted on a psychrometric chart.

Tolerance contours as shown in Robinson's data and in the results of the present investigation are affected by humidity as well as temperature since humidity lowers the tolerable temperature by limiting the rate of evaporation. Gagge (1937) has shown that for the nude human body, evaporation can be expressed by the formula:

$$E = w\mu\,(\epsilon T_s - rh \times \epsilon T_a)$$

where, E = evaporative loss (K.cal./ sq. meter/ hour)
w = per cent wettedness of body surface
μ = an evaporation constant, the value of which is unknown.

In exposures short of evaporative limits $w\mu$ and the vapor pressure gradient vary reciprocally, as determined by vapor pressure of the atmosphere. E, however, is limited by the w = 100 per cent , regardless of the vapor pressure, and $w\mu$, for specific conditions of air motion, direction, etc. has been determined by Gagge (1937) at approximately 30 K.cal. per square meter per hour per cm. Hg of vapor pressure gradient. Winslow et al. (1938) have defined the limits of evaporative regulation on the basis of this value for a range of vapor pressure gradients.

Appendix III
Discussion.

The w/μ concept has not been completely worked out for clothed subjects where insulation retards heat gain by radiation and convection and affects the evaporative function. Hence, empirical methods such as Robinson's based on physiological criteria have most commonly been used. In Figure 1, two of Robinson's tolerance contours, the 100 Index line and 175 Index line, have been plotted, together with the values of L determined in the present study. The slopes of the 100 Index and Line 1 agree very well, but the 175 Index line tends more toward the vertical than the AML lines. This lack of agreement cannot be explained with the data at hand, since Robinson's experiments did not extend beyond 120° F, and his method of computing tolerance contours is not adequately explained.

At extreme temperatures and/or humidities, symptoms occur which indicate that the temperature regulating system has failed to prevent critical rise in body temperature beyond the point of compensation. These terminal events in physiological breakdown are collectively known as heat stroke, of which three types are known, as follows; (1) sunstroke, (2) heat exhaustion, and (3) heat cramps. The first and third of these types are not pertinent to this investigation, respectively, because of lack of solar radiation, and because the duration of the tests was too short for critical salt depletion to occur. The second type, heat exhaustion, has been observed experimentally by several investigators, Taylor et al. (1943a) and (1943b), Bean and Eichna (1943), and Adolph (1943). The symptoms include nausea, vomiting, tachycardia, hypotension, vertigo, headache, dyspnea, anorexia, incoordination, and collapse. That these events are not due to simple dehydration has been shown in the studies of Taylor et al. (1943a), and Bean and Eichna (1943), whose subjects were allowed water <u>ad lib</u>. throughout the experiments. The diversity of symptoms suggests that when heat tolerance is exceeded, the physiological mechanisms which will be vitally affected vary to some extent with the individual. There is, however, much inferential evidence that circulatory failure is at the basis of most of the symptoms; that the essential feature is derangement of general circulation because of the demands made upon peripheral circulation by the heat loss mechanism.

In six of the Main Series tests subjects were forced to leave the hot room before the end of the scheduled hour. These tests were all made in environments at or above line 6 (Figure 1). None of the four subjects, whom it should be recalled had been given a four-day acclimatization prior to the series, displayed typical symptoms of heat exhaustion. The most common occurrences in addition to the measured physiological responses were moderate dyspnea and markedly flushed skin. The most notable subjective experiences were a sense of suffocation and weakness, and a deep-seated feeling of impending crisis. Under these conditions, though actual physiological collapse might not occur, preoccupation with the acute discomfort would go far to reduce the efficiency with which duties incident to piloting an airplane would be carried out.

Appendix III
Discussion.

With the exception of two men, whose symptoms will be described in the next section, the subjects in the 60- and 30-minute check series completed their exposure periods without either clearcut signs of heat exhaustion or feelings of intolerable discomfort. It is highly probable that the sitting position enables the withstanding of more extreme exposures without development of heat exhaustion than activities in the orthostatic position, because of lesser strain upon the cardiovascular system.

B. TWO CASES OF HEAT EXHAUSTION.

Among laboratory personnel who volunteered for tests, two enlisted men, Pvt. TA aged 38, and Sgt. RC aged 36, were forced to leave the hot room before the end of one hour's exposure because of symptoms of heat exhaustion. In both cases the tests were repeated with similar results. The exposure environments were approximately on line 5. Physiological data for the two tests on both subjects are plotted in Figure 8, together with the comparable average curves of the group in the 60-minute check series. It is first noted that the heart rate of RC is not remarkable, but that for TA, is accelerated much more rapidly than the average. Skin temperatures were not atypical, with the possible exception of the first test on TA. Rectal temperature rises were comparable with the group average. Sweat losses, based on only one determination for each subject, are within the range for the 60-minute group. Summarizing the evidence, it cannot be said that subject RC displays any abnormality in the functions measured. TA, while not abnormal in body temperatures and sweat loss, displayed a clearcut tendency to develop a rapid heart rate in the heat, reaching or exceeding 140 beats per minute, a value which is usually close to the limits of tolerance for sitting subjects in the present investigation.

The subjective symptoms were likewise different in the two subjects. TA reported faintness, scotomata, breathlessness and tingling in the hands, but did not appear in imminent danger of collapse before being removed from the hot room. RC became weak, pale, and slightly nauseated, but since he had not displayed an abnormal pulse trend, he was put in a prone kneeling position in the hope that he would revive while still in the hot room. These efforts were of little avail since on reassuming sitting position he again became faint. After leaving the hot room he was put down in bed and attended by a medical officer. Recovery was rapid and uneventful, and the man resumed his laboratory duties within a half hour. It is clear that these men possess constitutional or fitness divergencies which set them apart from the group.

C. SELECTION OF RECOMMENDED TOLERANCE LIMITS.

The results of the 60- and 30-minute check series (Appendix II) showed that the selected environments (lines 4 and 5) were not too extreme for all subjects, but two. Furthermore the physiological responses for these groups are within tolerable limits when compared with those in the

Main Series. The development of heat exhaustion in two men, however, urges caution in the selection of tolerance limits. Consequently, these environments must be listed as marginal and the next lower lines, 3 and 4, selected as tolerable. It should be noted that subjects TA and RC tolerated the environment of line 4 for 30 minutes, and could certainly tolerate line 3 for 60 minutes. Hence, the physiological classification as given in C. Conclusions, has been proposed as a basis for recommendation.

D. LIMITS OF HUMIDITY IN AIRCRAFT.

The tolerance limits defined in Figure 1 extend into ranges of humidity and vapor pressure which may not be expected to occur in aircraft. Air caught in the ventilating scoop will be heated adiabatically without change in absolute humidity or vapor pressures. This narrows the range of possible humidities at high temperature. It is therefore only necessary to determine the maximum vapor pressure to be expected in the atmosphere and give consideration to only those portions of the tolerance lines defined by this limiting vapor pressure.

Considerable study of the atmospheric vapor pressures in the various climates has shown that maximal values occur only in hot humid areas, the most extreme of which have been reported in India, Burma, and Indo-China*. Judged by average monthly temperature and humidity readings in these regions, the vapor pressure does not exceed 25 mm. Hg. However, it is possible that on some days this value might be exceeded, but it is doubtful that an absolute maximum would be higher than 30 mm. Hg.

Using this value as a limit, the tolerance limits may be expressed as temperatures at 30 mm. Hg or vapor pressure in order to simplify and reduce to one variable the recommendations. These limits, given in C. (2), it should be noted, are conservative, and at lower vapor pressures, higher temperatures can be tolerated, as defined by the tolerance lines.

* This information has kindly been supplied in a communication from Major Weldon F. Heald, Office of the Quartermaster General. He makes clear that the studies on which the conclusions are based are not yet completed, but all present information indicates that the stated maximum vapor pressures are correct.

Appendix III
Discussion.

E. REFERENCES CITED.

Adolph, E. F. and D. B. Dill, Am. J. Physiol. 123:369 (1938).

Robinson, S., E. S. Turrell, H. S. Belding, S. M. Horvath, Amer. J. Physiol. 140:168 (1943).

Taylor, H. L., A. F. Henschel, and A. Keys, Am. J. Physiol. 139:583 (1943)a; 140:439 (1943)b.

Robinson, S., E. S. Turrell, and S. D. Gerking, Rep. No. 12 to the Com. and Med. Res. NRC May 14, 1944.

Gagge, A.P., Am. J. Physiol. 120:277 (1937).

Winslow, C-E. A., L. P. Herrington, and A. P. Gagge, Am. J. Physiol. 124:692 (1938).

Bean, W. B. and L. W. Eichna, Fed. Proc. 2:144 (1943).

Adolph, E. F. Fed. Proc. 2:158 (1943).

TABLE I

SUBJECTS

	Name	Exp. No.	Age	Ht.	Wt.	Surface Area
Main Series:	Cutter	--	29	73	202	2.16
	Joffe	--	30	68	146	1.79
	Karpa	--	28	70	176	1.98
	Taylor	--	35	71	188	2.06
Check Tests:						
60 Min. Series	Spratt	1	31	68	142	1.76
	Rodbard	2	29	68	161	1.84
	Allen	3	35	72	197	2.10
	Piasecki	4	35	70	165	1.91
	Hall	5 - 9	35	68	153	1.82
	Taylor	6	35	71	189	2.05
	Jackson	7	35	69	145	1.79
	Marbarger	8	28	74	206	2.21
	Sadlowski	10	28	71	184	2.02
	Hartsough	11	21	67	130	1.68
	Radzinski	12	20	73	155	1.92
	Casbarro	13	25	67	133	1.69
Check Tests:						
30 Min. Series	Copeland	1	30	71	167	1.91
	Tokaji	2	29	68	144	1.77
	Smith	3	25	70	132	1.73
	Schacter	4	23	67	135	1.69
	Brookins	5	20	71	222	2.20
	Lee	6	23	68	115	1.60
	Shively	7	21	64	168	1.80
	Cutter	8	29	73	203	2.16
	Patt	9	29	66	145	1.75

TABLE II

ENVIRONMENTAL DATA: MAIN SERIES

Exp. No.	Dry Bulb	Wet Bulb	Relative Humidity	Vapor Pressure	N
1	158	93	7	16	3
2	149	95	14	27	3
3	140	88	12	18	4
4	131	104	40	45	3
5	125	94	31	31	4
6	124	84	21	20	2
7	115	92	40	30	2
8	113	96	57	46	3
9	111	84	31	21	2
10	110	92	51	32	4
11	108	105	88	54	3
12	106	102	88	51	4
13	106	100	81	47	3
14	100	88	62	31	2
15	96	92	86	39	4
16	92	72	34	13	4

TABLE III

PHYSIOLOGICAL DATA: MAIN SERIES

Exp. No.	Heart Rate	Skin Temp.	Rectal Temp.	Index (L)	Water Loss	Evap. Loss
1	147	101.7	100.1	1.20	562	369
2	129	101.4	100.6	1.00	627	386
3	107	98.7	98.9	- .55	511	280
4	136	101.6	100.4	1.09	664	295
5	119	101.2	99.8	.97	604	340
6	125	98.1	99.3	- .15	547	388
7	104	98.6	99.1	- .54	506	232
8	127	101.2	100.6	.93	517	272
9	106	97.2	99.2	- .70	307	228
10	98	97.6	98.9	- .90	425	168
11	136	101.5	100.6	1.15	692	236
12	131	100.6	99.8	.59	626	254
13	128	101.0	100.5	.88	618	162
14	92	97.5	98.7	- 1.11	248	71
15	91	98.5	98.2	- 1.15	156	76
16	82	95.6	98.0	- 1.60	108	105

TABLE IV

STATISTICAL SUMMARY: MAIN SERIES

	Mean	Std. Dev.	Range
Physiological Variables:			
Heart Rate	116.0	17.8	82 - 147
Skin Temperature	99.5	1.91	95.6 - 101.7
Rectal Temperature	99.5	0.85	98.0 - 100.6
Environmental Variables:			
(y) Dry Bulb Temperature	117.7	18.2	92 - 158
(z) Vapor Pressure of Air	32.5	12.8	13 - 54
Physiological Level: (x)	0.07	0.97	(-1.6) - (1.2)

Correlations:

Zero Order: $r_{xy} = .62$ Partial: $r_{xy \cdot z} = .97$

$r_{yz} = -.33$ $r_{yz \cdot x} = -.97$

$r_{xz} = .47$ $r_{xz \cdot y} = .95$

Multiple: $R_{x(yz)} = .94$

Regression Coefficients:

$B_{xy \cdot z} = .88$ $b_{xy \cdot z} = .047$

$B_{xz \cdot y} = .75$ $b_{xz \cdot y} = .057$

$$L = -7.31 + .047\ (\text{dry bulb}) + .057\ (\text{vapor pressure}) \pm .33$$

TABLE V

CHECK TESTS: 60-MINUTE SERIES

	DB	RH	VP	Water Loss (g/m²)	Storage (K.cal./m²)	Subject No.
	151	7	13.7	482	66.8	1
	151	7	13.7	355	95.5	2
	146	9	15.8	487	74.1	3
	146	9	15.8	594	74.9	4
	146	9	15.8	467	66.5	5
	131	24	28.3	319	79.6	6
	131	24	28.3	380	54.9	7
	116	48	37.6	372	73.7	8
	116	48	37.6	517	61.2	9
	117	47	38.1	618	78.9	10
	117	47	38.1	440	61.1	11
	104	90	49.8	430	66.8	12
	104	90	49.8	371	62.1	13
	104	90	49.8	445	78.0	14
Mean =	127			448.4	71.0	

HR					Skin Temperature					Rectal Temperature					Subj.
Pre	15	30	45	60	Pre	15	30	45	60	Pre	15	30	45	60	No.
80	98	112	125	140	93.0	100.4	100.4	100.5	100.7	98.5	99.3	99.5	100.7	100.7	1
80	88	101	115	126	90.9	100.5	100.6	101.2	102.2	98.3	98.5	99.0	99.6	100.4	2
84	108	108	112	132	94.2	101.6	101.3	101.5	101.1	98.5	98.7	99.2	100.0	100.6	3
84	100	104	120	140	93.2	98.9	99.5	99.6	100.4	97.7	97.4	98.2	98.8	99.6	4
80	106	108	120	120	92.3	101.0	100.7	100.4	100.5	99.4	99.2	99.6	99.8	100.9	5
80	96	100	102	112	92.7	100.3	99.2	98.9	100.3	98.6	99.7	99.4	99.5	101.2	6
76	92	100	104	116	90.5	99.9	99.7	98.9	100.0	99.6	99.4	99.4	99.4	99.8	7
78	96	96	112	124	91.8	100.1	99.4	98.4	99.8	98.4	98.5	98.8	99.3	99.9	8
72	80	88	96	104	93.0	99.6	99.9	99.0	100.6	99.0	98.9	99.4	99.9	100.4	9
72	92	108	108	108	92.1	100.4	100.4	100.2	100.9	99.0	99.0	99.5	100.2	100.8	10
76	108	116	140	144	93.6	99.9	100.5	100.3	101.1	99.2	99.4	100.0	100.8	101.2	11
70	92	100	100	112	93.5	100.3	100.5	101.0	101.6	98.9	99.0	99.6	100.5	101.7	12
92	94	112	108	108	93.1	103.3	102.3	101.9	101.8	100.2	99.8	100.2	100.8	101.6	13
80	100	112	128	136	94.1	100.1	100.1	100.6	100.4	97.0	98.3	99.0	100.0	100.8	14
78.8	96.4	104.6	113.6	123.0	92.4	100.4	100.2	100.2	100.8	98.7	99.0	99.3	100.0	100.7	= Mn

TABLE VI

CHECK TESTS: 30-MIN. SERIES

Subj. No.	DB	RH	VP	Wt. Loss (g/m^2)	Storage ($Kcal/m^2$)	H R			Skin Temperature			Rectal Temperature		
						Pre	15	30	Pre	15	30	Pre	15	30
1	154	10	21.2	252.0	79.3	66	96	120	91.3	102.4	101.7	98.8	99.4	100.0
2	154	10	21.2	225.7	73.5	88	116	128	93.4	102.2	102.4	98.7	99.5	100.7
3	154	10	21.2	343.8	69.3	69	88	112	93.7	102.9	102.7	98.2	99.1	100.3
4	128	40	43.4	236.4	78.7	92	112	136	92.6	103.2	100.4	97.8	101.0	101.0
5	128	40	43.4	491.1	80.0	80	112	136	93.0	100.9	101.9	99.6	100.0	100.7
6	128	40	43.4	266.7	46.0	80	116	140	94.4	100.0	101.1	99.2	100.0	100.4
7	110	80	52.4	330.4	71.2	72	124	136	91.6	100.7	101.2	99.6	99.9	100.5
8	110	80	52.4	445.6	78.0	88	128	128	91.5	101.1	101.8	98.4	100.0	100.7
9	110	80	52.4	181.1	53.7	72	126	120	92.1	101.4	101.5	99.4	99.5	100.3
Mean				308.1	69.9	78.5	111	128	92.6	101.6	101.6	98.9	99.8	100.5

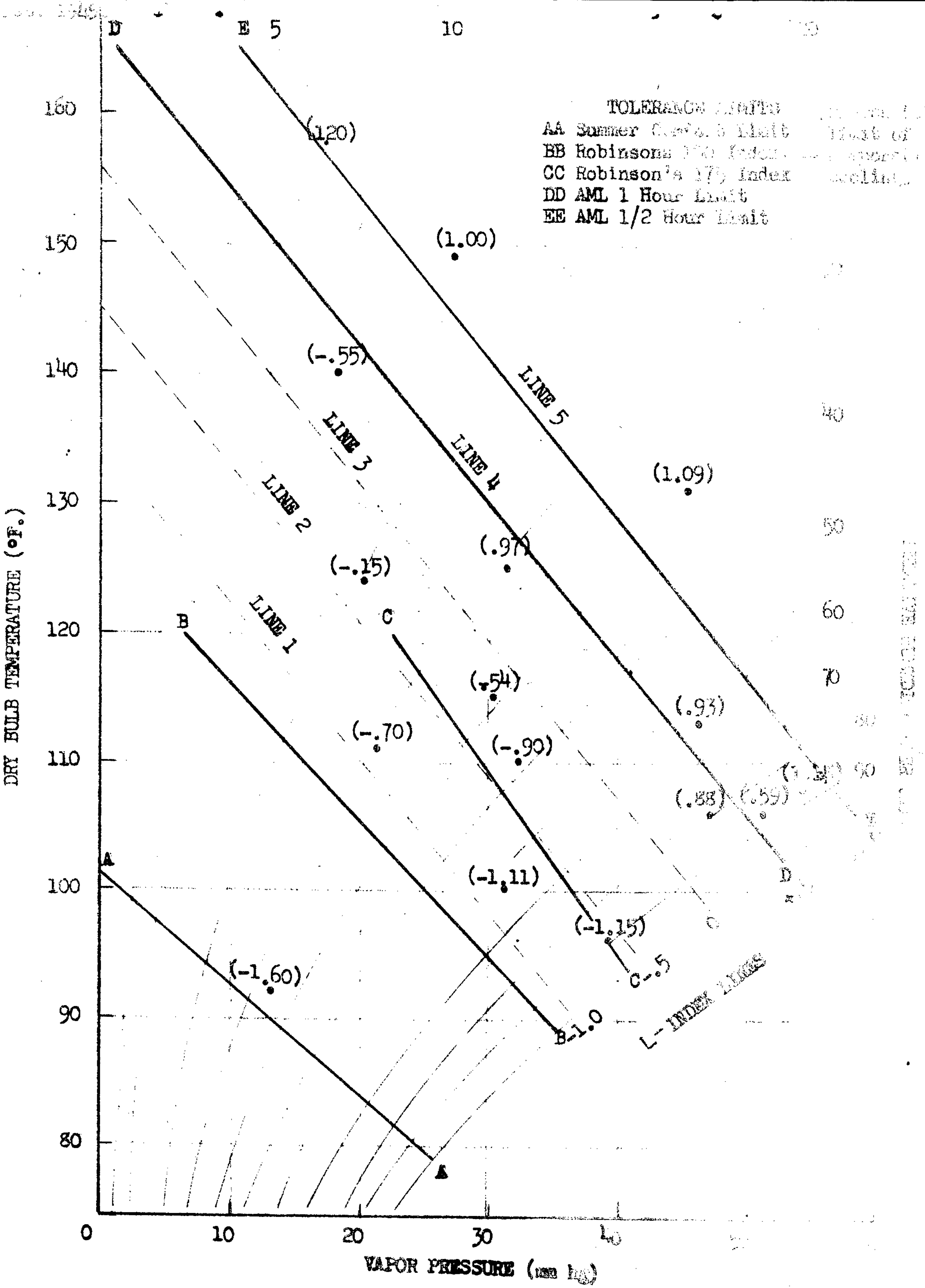

FIGURE 1. TOLERANCE CONTOURS.

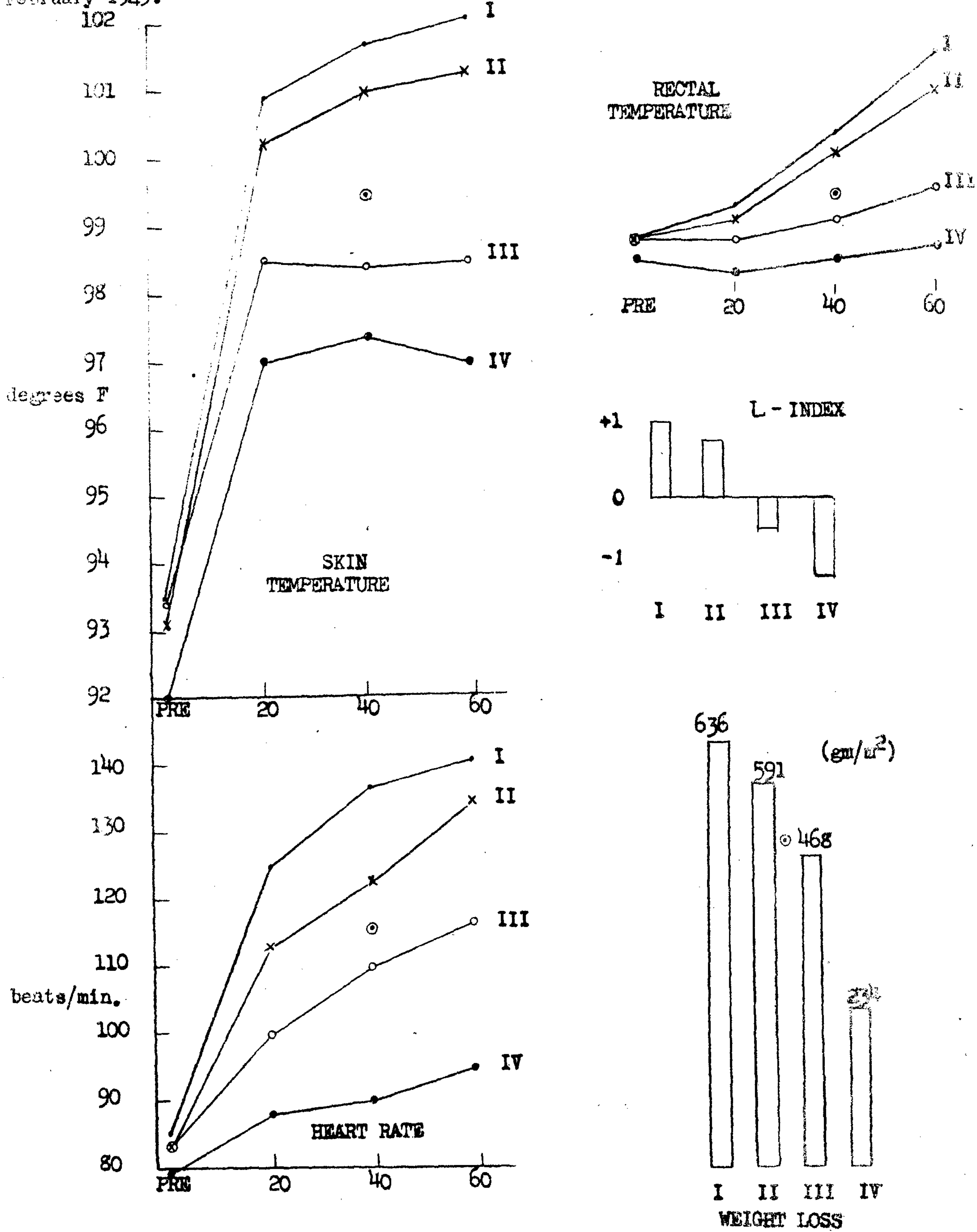

FIGURE 2

MAIN SERIES: AVERAGE DATA.

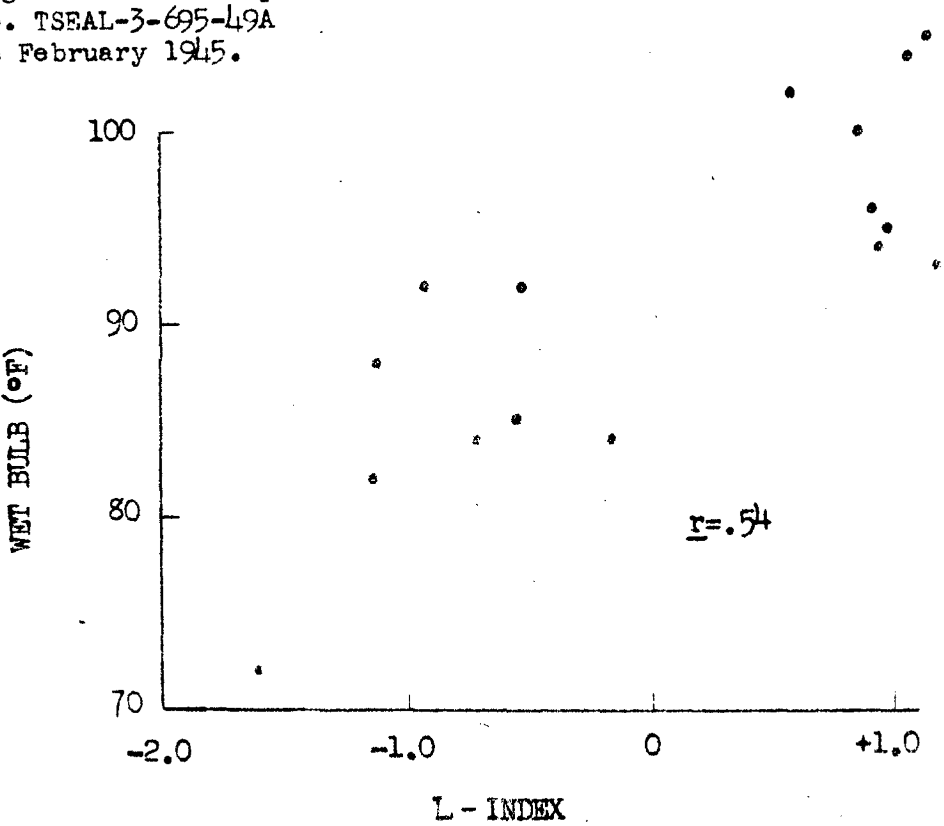

Figure 3 MAIN SERIES: WET BULB.

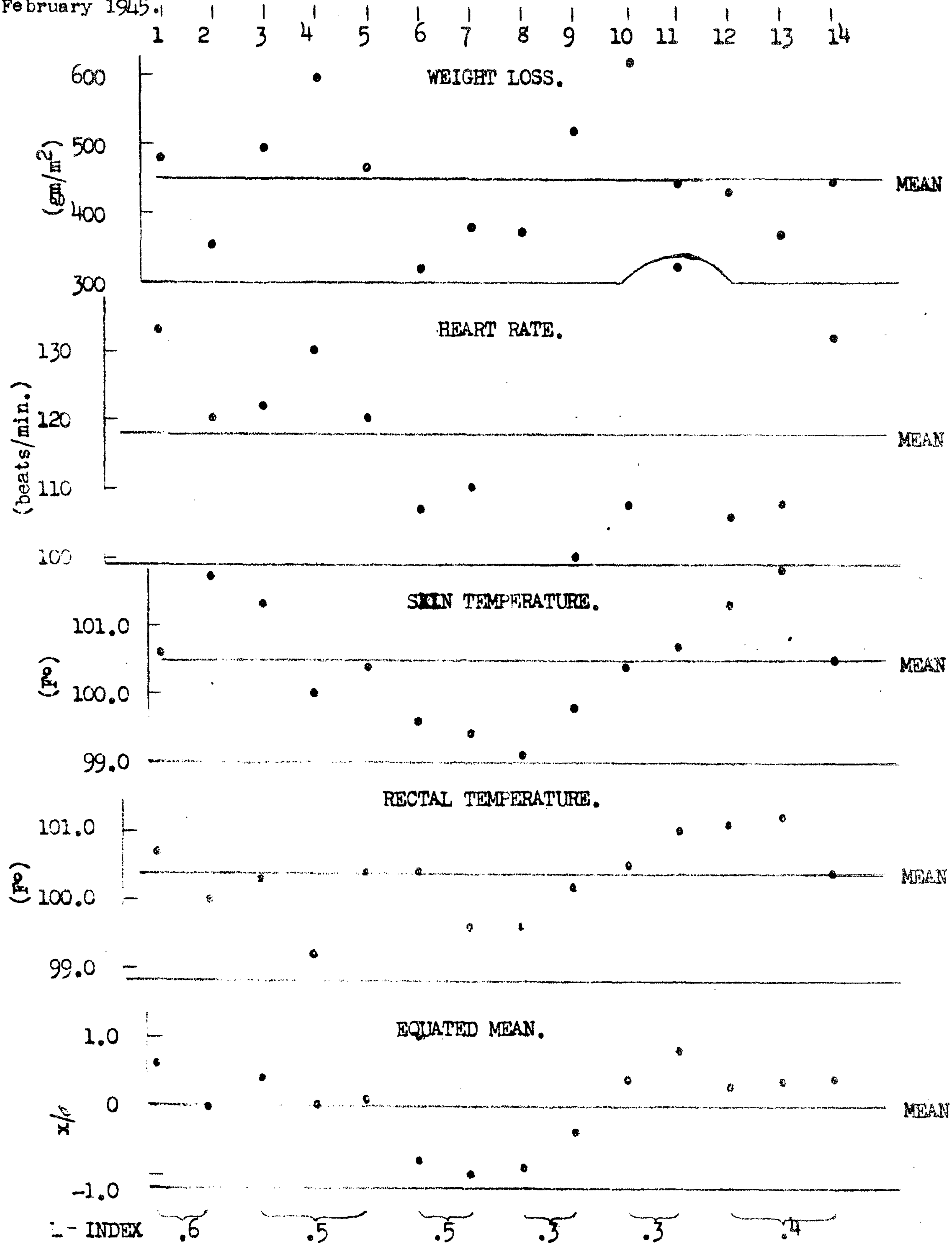

FIGURE 4. CHECK TESTS: 60 MINUTE SERIES.

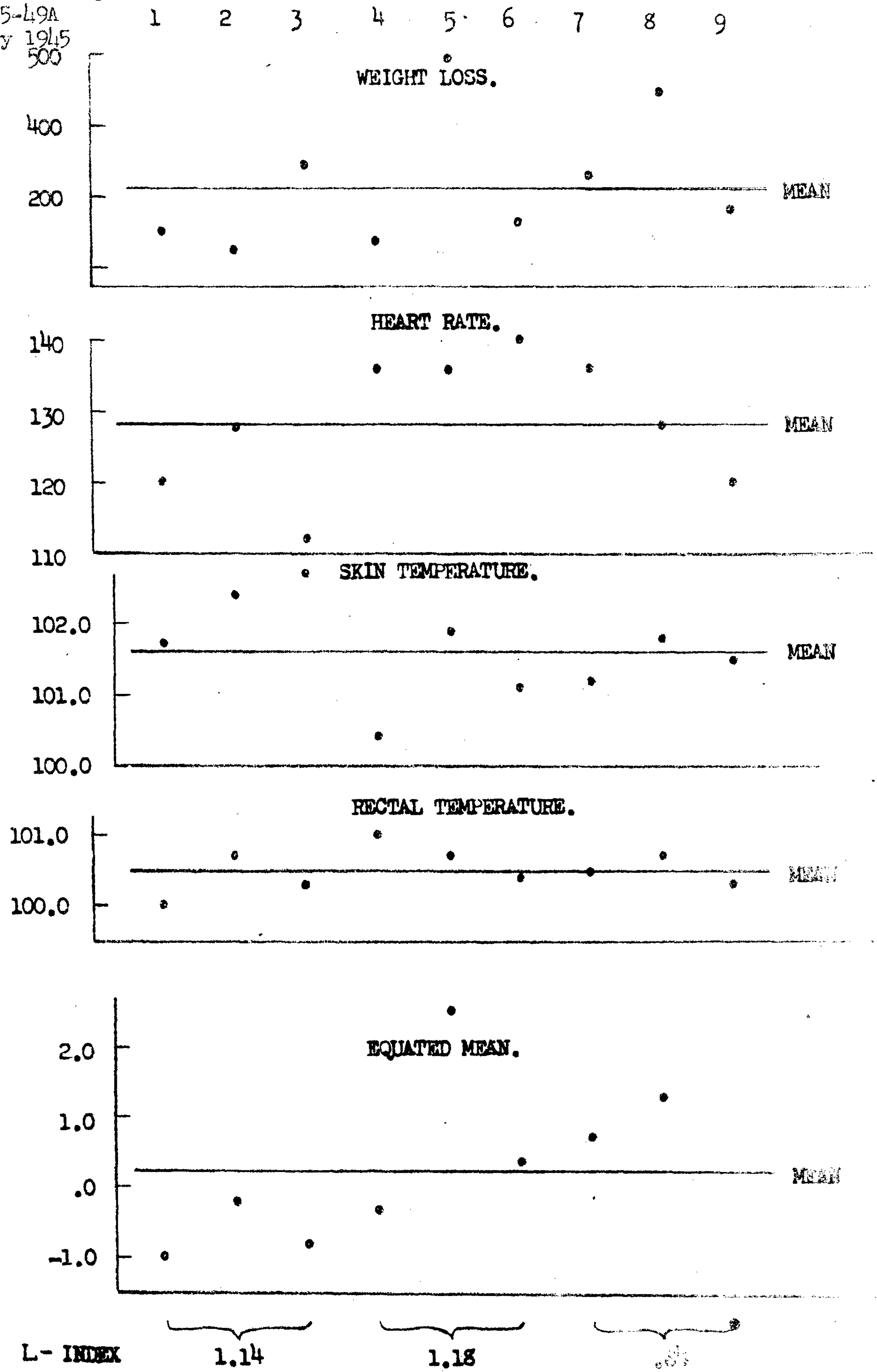

FIGURE 5. CHECK TESTS: 30 MINUTE SERIES.

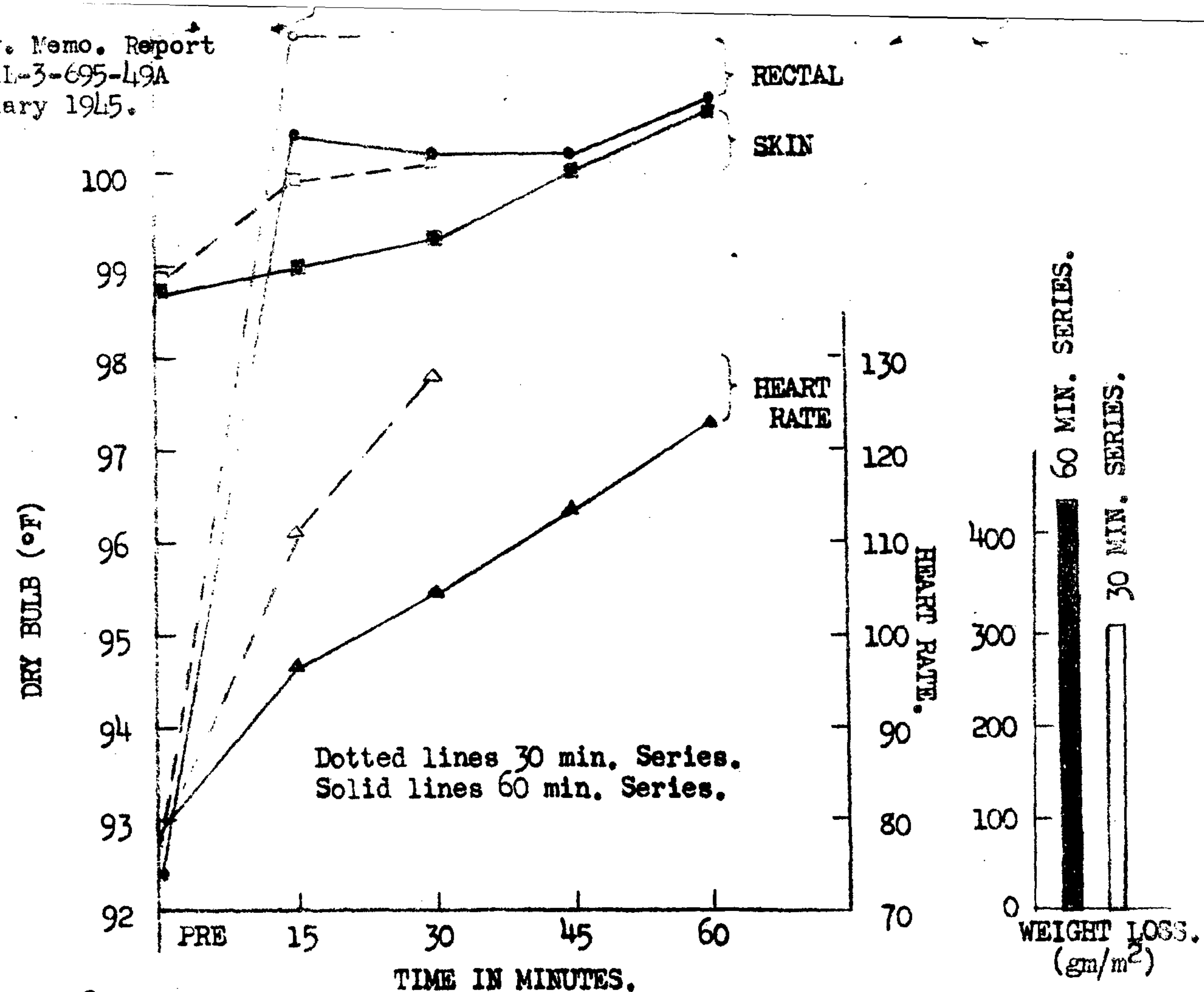

Figure 6. CHECK TESTS.

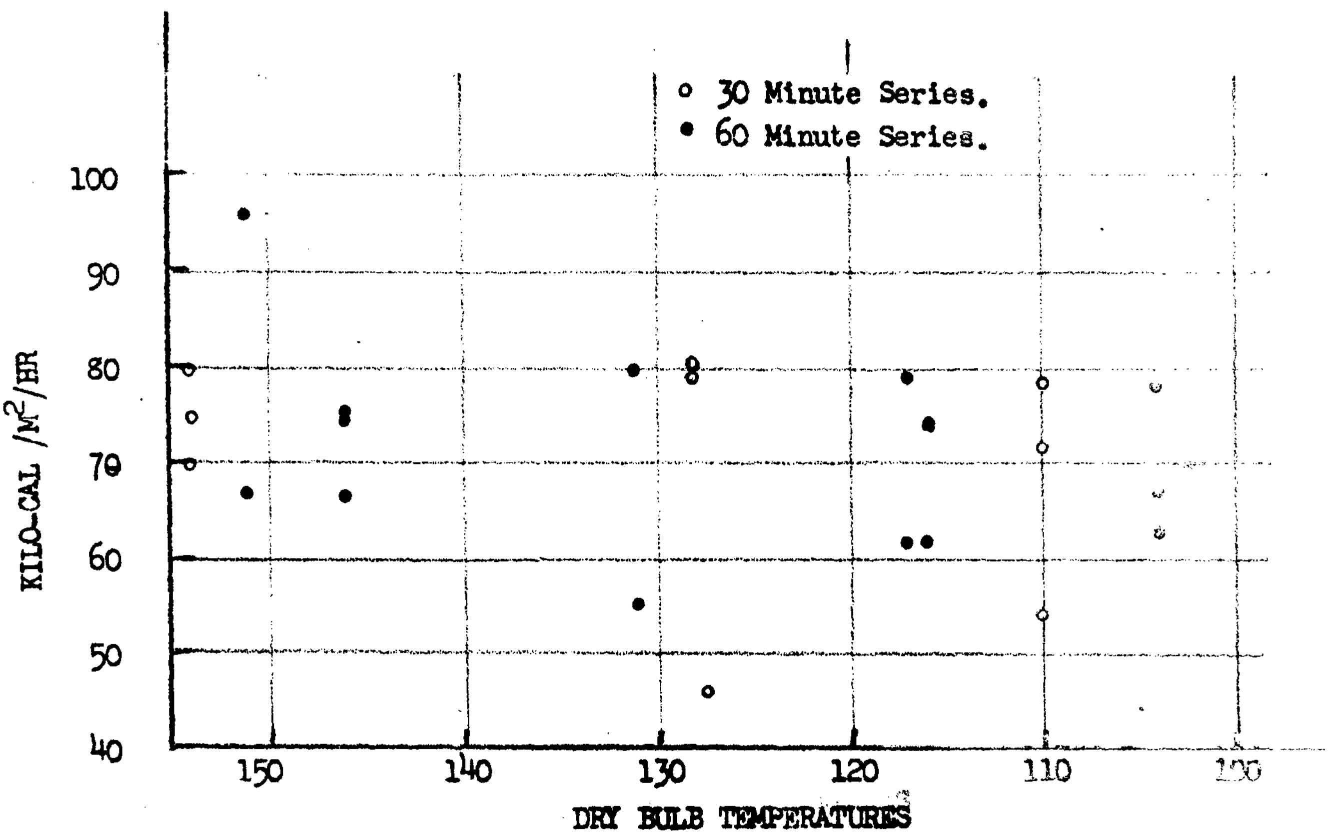

FIGURE 7: STORAGE CHANGES: 30 AND 60 MINUTE SERIES.

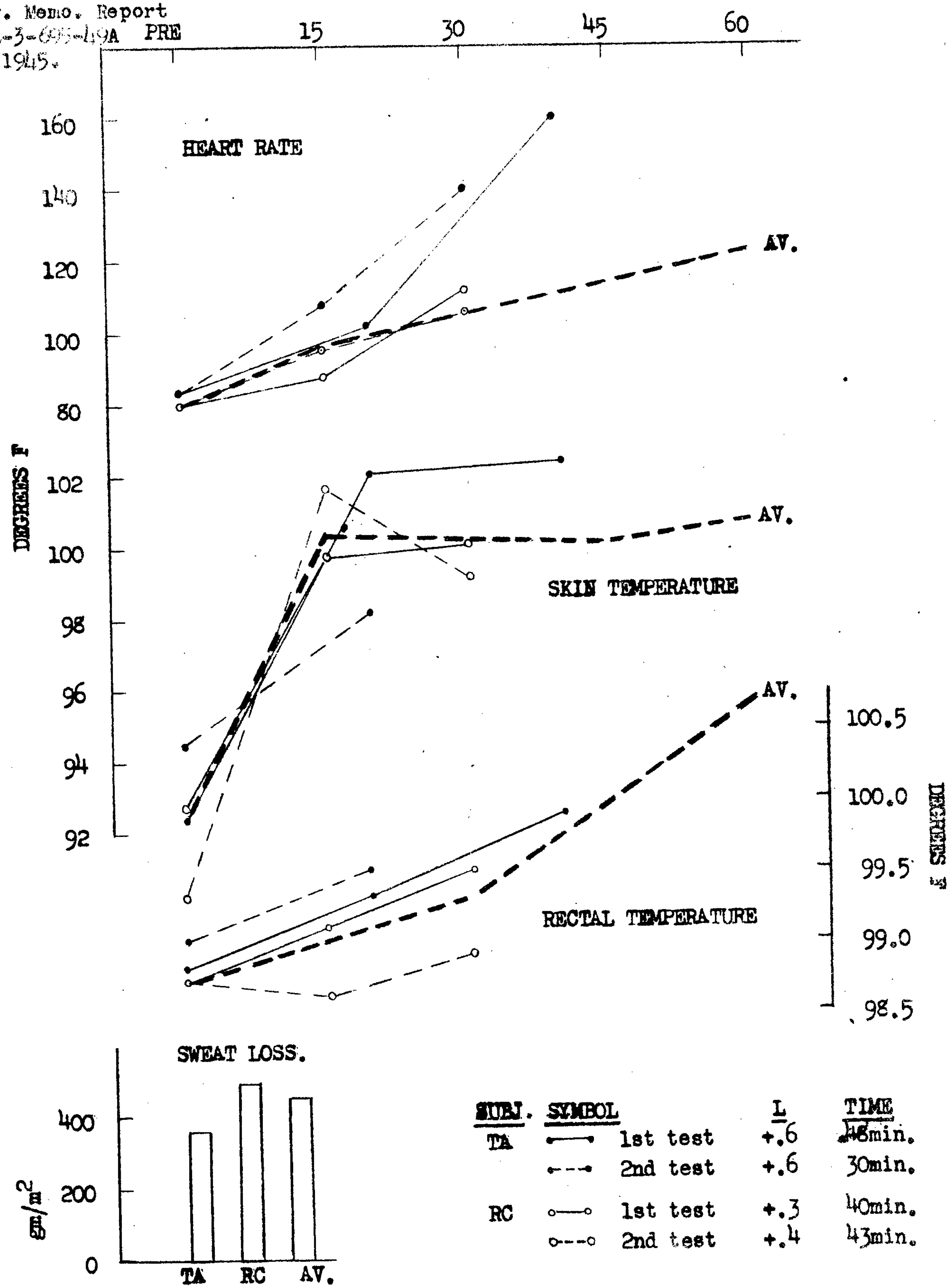

FIGURE 8: RESPONSES OF SUBJECTS TA AND RC IN HEAT EXHAUSTION.